Quarterly Research Performance Progress Report

Federal Agency to which the report is submitted	Office of Fossil Energy
FOA Name	Environmentally-Prudent Unconventional Resource Development
FOA Number	DE-FOA-0001076
Nature of the Report	Research Performance Progress Report (RPPR)
Award Number	DE-FE0024314
Award Type	Cooperative Agreement
Name, Title, Email Address, and Phone Number for the Prime Recipient	**Technical Contact (Principal Investigator):** Melissa Poerner, P.E., Senior Research Engineer, melissa.poerner@swri.org, 210-522-6046 **Business Contact:** Jennifer Bigler, Associate Specialist, jennifer.bigler@swri.org, 210-522-3179
Prime Recipient Name and Address	Southwest Research Institute 6220 Culebra Road, San Antonio, TX 78238-5166
Prime Recipient type	Not for profit organization
Project Title	**TA2 Development and Field Testing Novel Natural Gas Surface Process Equipment for Replacement of Water as Primary Hydraulic Fracturing Fluid**
Principal Investigator(s)	Melissa Poerner, P.E., Klaus Brun, Ph.D., and Kevin Hoopes – *SwRI* **Subcontractor and Co-funding Partner**: Sandeep Verma, Ph.D. – *Schlumberger*
Prime Recipient's DUNS number	00-793-6842
Date of the Report	August 8, 2015
Period Covered by the Report	April 1, 2015 – June 30, 2015
Reporting Frequency	Quarterly
Signature of Principal Investigator:	Melissa Poerner Melissa Poerner, P.E.

TABLE OF CONTENTS

1 INTRODUCTION

Southwest Research Institute® (SwRI®) and Schlumberger Technology Corporation (SLB) are working to jointly develop a novel, optimized, and lightweight modular process for natural gas to replace water as a low-cost fracturing medium with a low environmental impact. Hydraulic fracturing is used to increase oil and natural gas production by injecting high-pressure fluid, primarily water, into a rock formation, which fractures the rock and releases trapped oil and natural gas. This method was developed to increase yield and make feasible production areas that would not otherwise be viable for large-scale oil and natural gas extraction using traditional drilling technologies.

Since the fracturing fluid is composed of approximately 90% water, one of the principal drawbacks to hydraulic fracturing is its excessive water use and associated large environmental footprint. Each application of fracturing can consume as much as three to seven million gallons of water. During the fracturing process, some of the fracturing fluid is permanently lost and the portion that is recovered is contaminated by both fracturing chemicals and dissolved solids from the formation. The recovered water or flow-back, represents a significant environmental challenge, as it must be treated before it can be reintroduced into the natural water system. Although there is some recycling for future fracturing, the majority of the flow-back water is hauled from the well site to a treatment facility or to an injection well for permanent underground disposal.

To mitigate these issues, an optimized, lightweight, and modular surface process using natural gas to replace water will be developed and field-tested as a cost-effective and environmentally-clean fracturing fluid. Using natural gas will result in a near zero consumption process, since the gas that is injected as a fracturing fluid will be mixed with the formation gas and extracted as if it were from the formation itself. This eliminates the collection, waste, and treatment of large amounts of water and reduces the environmental impact of transporting and storing the fracturing fluid.

There are two major steps involved in utilizing natural gas as the primary fracturing medium: (i) increasing the supply pressure of natural gas to wellhead pressures suitable for fracturing and (ii) mixing the required chemicals and proppant that are needed for the fracturing process at these elevated pressures. The second step (natural gas-proppant mixing at elevated pressures) still requires technology advancements, but has previously been demonstrated in the field. However, the first step (a compact on-site unit for generating high-pressure natural gas (supercritical methane (sCH_4)) at costs feasible for fracturing) has not been developed and is currently not commercially available. The inherent compressibility of natural gas results in significantly more energy being required to compress the gas than is required for pumping water or other incompressible liquids to the very high pressure required for downhole injection.

This project aims to develop a novel, hybrid method to overcome this challenge. Several processes will be evaluated to identify the optimal process for producing high-pressure natural gas (sCH_4). Initial calculations have shown a substantial reduction in the total topside process energy requirements if a low-yield Liquefied Natural Gas (LNG) expansion, instead of a refrigeration production process, is utilized and treatment is limited to removal of only the minimal amount of impurities. The project will develop, optimize, and test this process both in the lab and in the field.

The project work will be performed in three sequential phases. The first phase will start with a thorough thermodynamic, economic, and environmental analysis of potential concepts, as well as detailed design. This will allow the selected thermodynamic pathway to be optimized for the intended application. The second phase will consist of the assembly and testing of a reduced-scale model in an SwRI laboratory to measure the overall efficiency and cost savings of the developed process. The third and final phase will be an onsite demonstration conducted in close partnership with SLB. This will allow the real world benefits of the technology to be demonstrated and quantified.

This report covers the work completed in this budget quarter. The project goals and accomplishments related to those goals are discussed. Details related to any products developed in the quarter are outlined. Information on the project participants and collaborative organizations is listed and the impact of the work done during this quarter is reviewed. Any issues related to the project are outlined and lastly, the current budget is reviewed.

2 ACCOMPLISHMENTS

2.1 *Project Goals*

The primary objective of this project is to develop and field test a novel approach to use readily available wellhead (produced) natural gas as the primary fracturing fluid. This includes development, validation, and demonstration of affordable non-water-based and non CO_2-based stimulation technologies, which can be used instead of, or in tandem with, water-based hydraulic fracturing fluids to reduce water usage and the volume of flow-back fluids. The process will use natural gas at wellhead supply conditions and produce a fluid at conditions needed for injection.

The project work is split into three budget periods. Each budget period consists of one year. The milestones for each budget period are outlined in Table 2.6. This table includes an update on the status of that milestone in relation to the initial project plan. Explanations for deviations from the initial project plan are included.

2.2 *Accomplishments*

2.2.1 Cycle Analysis

The cycle analyses were considered confidential and therefore, are not included in this report.

2.2.2 Cycle Selection

The cycle scoring was considered confidential and therefore, is not included in this report. The final cycles selected for future analysis include:

- Direct Compression
- Pre-Compressed Methane Liquefaction
- Mixed Refrigerant

2.2.3 Commercial Equipment Specification and Availability

Efforts to identify commercially available equipment for the analyzed cycles and to obtain budgetary quotations for the equipment continued during the previous quarter. The primary goals of these efforts were:

- To determine whether the equipment modeled in the analysis was commercially available
- To identify operational limitations for the equipment
- Obtain budgetary pricing for the equipment

In the following paragraphs, equipment quotations and/or specifications obtained during the past quarter are summarized.

2.2.3.1 *Compressors*

Direct Compression Cycle

In the *direct compression* cycle first reported on in second quarter report, the process diagram indicated three stages of compression. Since that report, discussions with compressor manufacturers have resulted in a modified compressor configuration that may be better able to handle the large pressure ratio and volumetric reduction of the gas in the direct compression process. The updated configuration utilizes a centrifugal compressor to provide two initial stages to boost the methane pressure from the assumed 500 psia inlet to the required 1,900 psia. Next, four reciprocating compressors operating in parallel provide two final stages of compression with intercooling and after-cooling. The machines would boost methane pressure from 1,900 psia to the final 10,000 psia. This updated process is diagramed in Figure 2-1 below. Specifics about the centrifugal and reciprocating compressors are given in the following paragraphs.

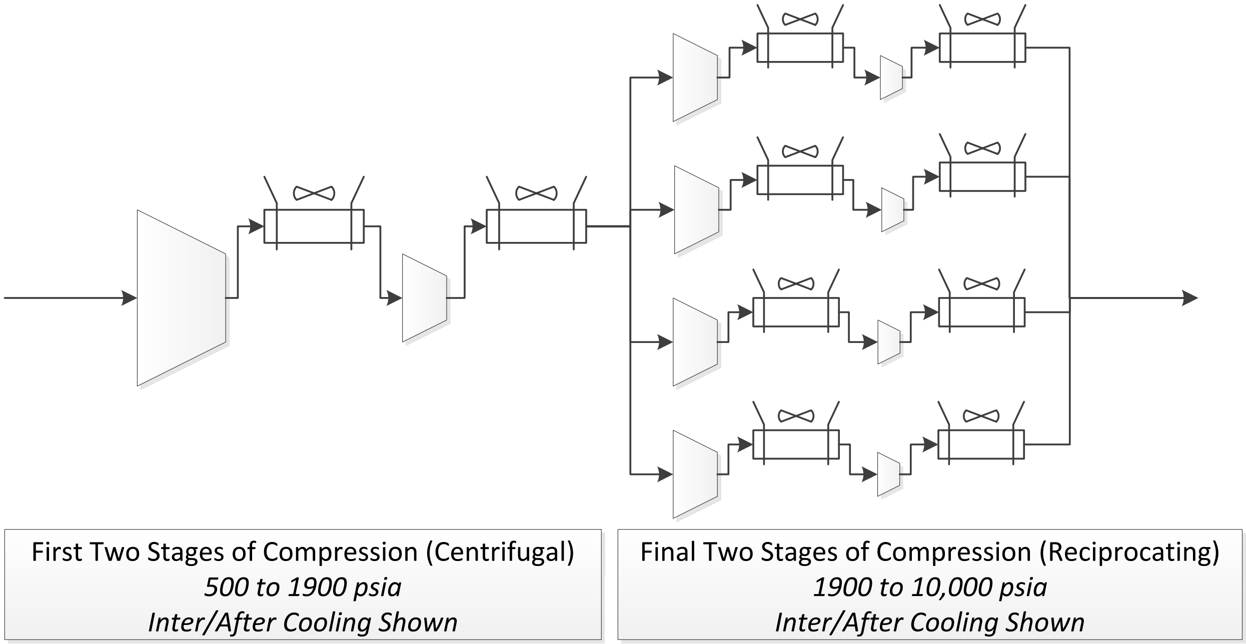

Figure 2-1. Schematic of Direct Compression Process Utilizing Centrifugal and Reciprocating Compressors

<u>Centrifugal Compressor</u>

Dresser-Rand provided a preliminary performance specification for a centrifugal compressor to be utilized in the *Direct Compression* process. The specified centrifugal compressor, model# D4R8B, would be utilized to boost the inlet flow of methane from 500 psia to 1,900 psia and would be used in series with the Ariel reciprocating compressors described in a following paragraph. The specified machine would utilize an axially-split configuration (similar to the compressor shown in Figure 2-2 below), eight impellers separated into two stages of compression with intercooling between stage one and two. The specified compressor has polytropic efficiencies of 83.3% and 82.2% for the first and second stages of compression, respectively. Power required for the machine, excluding losses, is approximately 7.45 MW.

Specific sizing information was not provided at the time of this reporting. General sizing information indicates that the compressor, not including required auxiliary equipment, would have a maximum footprint of 35 inch by 54 inch and a maximum weight of 13,800 lb_m. Budgetary quotes were not provided at the time of this reporting.

Figure 2-2. Typical Dresser-Rand DATUM® Series Centrifugal Compressor

Reciprocating Compressor

Ariel Corporation provided a preliminary performance specification for a reciprocating compressor to be utilized for the final two stages of the *Direct Compression* process. The specified compressor, model# JGF/4, would utilize a four-throw configuration to compress methane from 1,900 psia to an outlet pressure of approximately 10,000 psia. In this configuration, an additional machine would be required to achieve the initial pressure boost from 500 psia to 1,900 psia. Figure 2-3 below displays a typical Ariel reciprocating compressor with four throws.

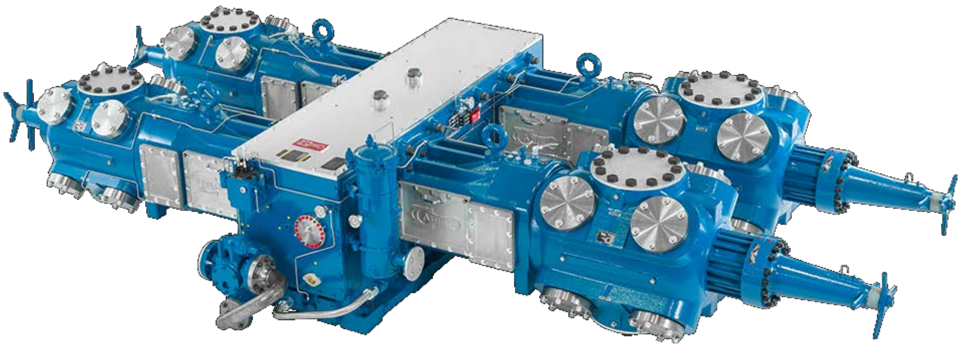

Figure 2-3. Typical Ariel JGF/4 Reciprocating Compressor

The *Direct Compression* process mass flow rate, which is approximately 220,000 lb_m/hr, exceeds the specified flow rate of the Ariel JGF/4 of 53,200 lb_m/hr. To accommodate the full flow rate, four of the Ariel JGF/4 machines would be required. The total power for the four machines is approximately 6.2 MW.

The second-stage cylinder would require additional design and development due to a current maximum allowable working pressure (MAWP) specification of 9,090.9 psig.

Budgetary quotes had not been obtained for these compressors at the time of this reporting.

2.2.3.2 Coolers

Direct Compression Cycle

Harsco Industrial Air-X-Changers provided sizing, performance, and budgetary pricing estimates for dry air coolers to be utilized in the *Direct Compression* process for compressor inter-stage and after-cooling. Each of the specified coolers rejects heat at a rate of approximately 1.8 to 2.0 MW. The specified units have width, length, and height of 8 ft, 39 ft, and 9.75 ft (respectively) and weigh approximately 25,500 lb_m.

To handle the full heat load of the *Direct Compression* process (24 MW), a total of 12, truck-mounted coolers would be required for a total capital investment of approximately $2,000,000. Some of the key specifications for the coolers are given below Table 2.1. Because the process would require four coolers at each stage, single unit and total values of *cost* and *heat exchanged* are given.

Table 2.1. Harsco Air Cooler Specification Summary

	Cooler 1	Cooler 2	Cooler 3
Gas Side Pressure (psia)	2,100	4,600	9,500
Heat Exchanged/Unit (MW)	1.9	1.9	1.7
Total Rate of Heat Exchanged (MW)	7.8	7.7	7.0
Length (ft)	39	39	39
Width (ft)	8	8	8
Height (ft)	9.8	9.8	9.8
Weight (lb_m)	24,900	25,500	25,500
Cost/Unit ($)	128,000	157,000	218,000
Total Cost ($)	511,000	629,000	872,000

2.2.3.3 Heat Exchangers

Direct Compression Cycle

Heat Exchanger Design

Heat Exchanger Design, Inc. (HED, Inc.) provided sizing, performance, and budgetary estimates for three shell-and-tube heat exchangers to be utilized in the *Direct Compression* process. The heat exchangers were all sized to cool the full methane flow between and after compression stages. The sizing calculations assumed water on the shell side of the heat exchanger entering at 85 °F.

In total, the three heat exchangers would require a cooling water flow rate of approximately 3,800,000 lb_m/hr (7,600 gpm). The cooling water would require evaporative coolers and the requisite auxiliary equipment (e.g., pumps) to reject heat to the atmosphere. The estimated total cost for the exchangers is $1,320,000. Some of the key specifications of the three heat exchangers are given below in Table 2.2 (note that all values are approximate).

Table 2.2. HED, Inc. Heat Exchanger Specification Summary

	HX 1	HX 2	HX3
Gas Side Pressure (psia)	2,100	4,600	10,000
Rate of Heat Exchanged (MW)	6.7	7.3	6.5
Cooling Water Flow (lb_m/hr)	2,280,000	791,000	707,000
Length (ft)	30	30	35
Width (ft)	3.2	3	6.7
Height (ft)	7	6	7.3
Weight (lb_m)	30,800	29,000	54,900
Cost ($)	214,000	263,000	846,000

Heatric

Heatric provided preliminary sizing, performance, and budgetary estimates for three printed-circuit heat exchangers (PCHE). Like the HED, Inc. heat exchangers described above, the Heatric PCHEs were sized for inter-stage and after-cooling of the *Direct Compression* process. The performance and sizing calculations were generated using water as the coolant with inlet and outlet temperatures of 85°F and 95°F, respectively.

In total, these three heat exchangers would require a cooling water flow rate of approximately 6,910,000 lb_m/hr (13,800 gpm). Unlike the shell-and-tube exchangers, the PCHEs would require a clean source of water so as to avoid particle deposition in the exchanger paths. The level of purity has not yet been specified but it is likely filtration methods and chemical treatment methods would be required.

The dimensional and weight estimates provided by Heatric do not include connections and manifolds and are, therefore, anticipated to increase. It should be noted that even with a large increase in the size/weight values, the Heatric PCHEs would still represent a minimal impact to the process footprint.

Table 2.3. Heatric Heat Exchanger Specification Summary

	HX 1	HX 2	HX3
Gas Side Pressure (psia)	2,100	4,600	10,000
Rate of Heat Exchanged (MW)	6.8	7.2	6.4
Cooling Water Flow (lb_m/hr)	2,270,000	2,450,000	2,190,000
Length (ft)	8	6.7	7.8
Width (ft)	3.3	3.7	4.1
Height (ft)	3.8	4.5	5.5
Weight (lb_m)	4,850	6,730	15,400
Cost ($)	250,000	328,000	593,000

2.2.3.4 Expander

The expander selection is considered confidential and therefore is not included in this report.

2.2.4 Cycle Exergy Analysis

During the analysis of the various thermodynamic cycles, it was important to understand the minimum amount of energy that was needed to take a natural gas from the inlet process conditions to the outlet process conditions. In addition, it was important to know how the use of natural gas compared to the use of water for fracturing from an energy standpoint. An exergy analysis was conducted to meet these two goals. The details of the analysis and its results are discussed below.

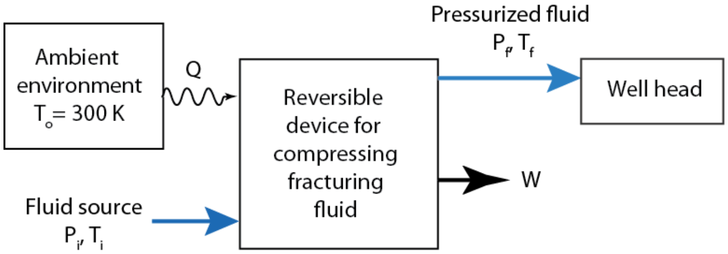

Figure 2-4: Simple Black Box representation of the Devices to be analyzed. P and T are the Pressures and Temperatures of the Flowing Fluid

2.2.4.1 Exergy Analysis

The proposed process is to use natural gas (methane) where other local wells are used as the source of the gas.

In the figure above, a low-pressure working fluid is compressed reversibly to high pressure. This fluid is then injected into a well. The minimum work required for the device can be determined using the first and second laws and assuming all processes are reversible. The device is allowed to thermally interact (Q) with the ambient environment at 80.3 °F (300 K). It is presumed that the volume of the device does not change and that the system operates in steady state. (This simple analysis does not take into account the charging process of the well where the internal pressure of the well increases as more fluid is pumped into it.) In addition, the wellhead is presumed to remain at constant pressure. Equation 13 shows the result where W is the rate of work transfer from the device, m is the mass flow rate of the working fluid, h_i and h_f are the enthalpy of the inlet stream and outlet streams, respectively, s_i and s_f are the entropies of the inlet stream and outlet streams, respectively, and T_o is the ambient temperature. The result is not surprising; it states that the work required is the difference of exergy flows into and out of the device.

$$\frac{W}{m} = (h_i - T_o s_i) - (h_f - T_o s_f) \tag{13}$$

The appropriate metric of comparison for various working fluids is the work required to fracture a well of fixed volume. This quantity can be estimated using the work per unit volume of fluid pumped into the wellhead, $\rho_f W/m$, or where ρ_f is the density of the working fluid entering the wellhead.

$$\rho_f \frac{W}{m} = \rho_f\left[(h_i - T_o s_i) - (h_f - T_o s_f)\right] \tag{14}$$

Equation 14, combined with appropriate equations of state, allows the comparison of the merits of various fluids under various source conditions. Water and methane are analyzed as shown in Figure 2-5. The water calculations are used to provide a baseline for comparing the methane results.

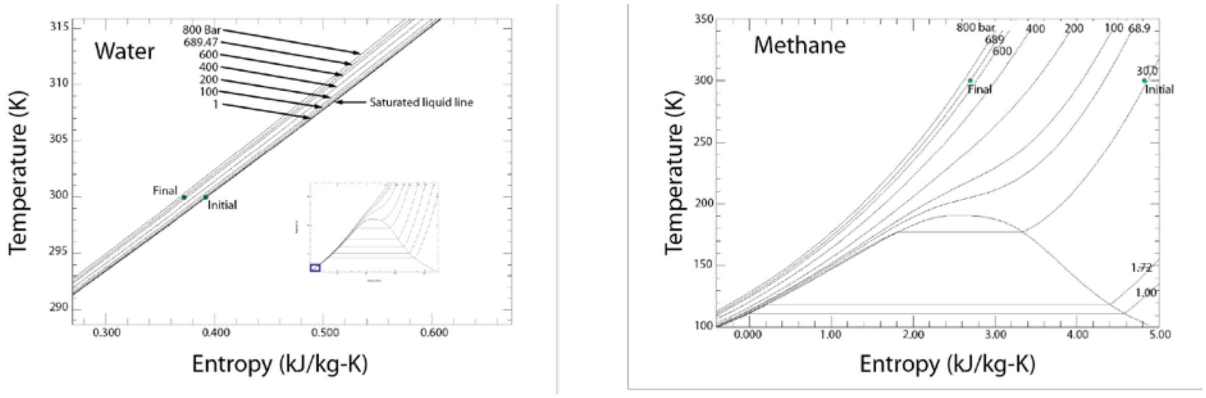

Figure 2-5. T-s Diagram for Water and Methane. The Green initial and Final points are the State Points used for the calculations described in the text

Equation 13 determines the energy per unit mass pumped into the wellhead. The equations of state for water and methane used in the following calculations are those provided by the REFPROP program, available from NIST. The T-s diagrams for water and methane are shown in Figure 2-5.

The choice of the initial states is dictated by the state of the fluid supplies. For water, the initial state, shown on the left in Figure 2-5, is assumed liquid at a temperature of 80.3°F (300 K) and pressure of 14.5 psia (1 bar). For methane, a 500 psia (34.5 bar) and 80.3°F (300 K) gas supply from another well is used a source as shown on the right in Figure 2-5. The final states for the water and methane cases are the same at 80.3°F (300 K) and 10,000 psia (689.5 bar). Table 2.4 contains a listing of properties of both methane and water for these initial and final states.

Using these properties and Equation 13, the minimum work for compressing and injecting methane or water into the well to be fractured is 189.8 Btu/lb$_m$ (441.4 kJ/kg) methane and 29.3 Btu/lb$_m$ (68.1 kJ/kg) water, respectively. On a per unit mass of material basis, methane has an energy requirement that is 6.48 times that of water. As already discussed, a better performance metric is the work per unit volume of fluid pumped into the wellhead, which is 3,615 Btu/ft^3 (134.7 MJ/m^3) for methane and 1,873 Btu/ft^3 (69.8 MJ/m^3) for water. On this per unit volume basis, methane only requires about 1.93 times the work required to pump water into the well.

Table 2.4. Properties of Initial and Final States for Methane and Water as shown on Figure 2-5

Methane

State	Temperatur (K)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Exergy (kJ/kg)		To (K)	h-To s (kJ/kg)	Min W (kJ/kg)	Min W (kJ/m³)
1 (initial)	300	34.474	23.502	881.1	4.7793	1249.6		300	-552.69		
2 (final)	300	689.47	305.14	698.16	2.6983	1687.1		300	-111.33	-441.36	**-134676.59**

Water

State	Temperatur (K)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Exergy (kJ/kg)		To (K)	h-To s (kJ/kg)	Min W (kJ/kg)	Min W (kJ/m³)
1 (initial)	300	1	996.56	112.65	0.39306	158.72		300	-5.268		
2 (final)	300	689.47	1025.4	174.47	0.37218	226.76		300	62.816	-68.084	**-69813.334**

Wmethane/W water (per unit mass)	6.483
Wmethane/W water (per unit vol)	1.929

Table 2.5. Properties of Methane for Compression from 14.5 psia (1 bar), 80.3 °F (300 K)

Methane from 1 bar, 300 K

State	Temperature (K)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Exergy (kJ/kg)		To (K)	h-To s (kJ/kg)	Min W (kJ/kg)	Min W (kJ/m³)
1 (initial)	300	1	0.64425	914.1	6.6951	711.35		300	-1094.43		
2 (final)	300	689.47	305.14	698.16	2.6983	1687.1		300	-111.33	-983.1	**-299983.13**

W methane/W water (per unit mass)	14.440
W methane/W water (per unit vol)	4.297

The energy requirement for the methane becomes much higher if the source of methane is assumed to be at 14.5 psia (1 bar) and 80.3 °F (300 K). Table 2.5 contains the relevant properties of methane and using Equations 13 and 14, the minimum work is determined to be 422.7 Btu/lb$_m$ (983.1 kJ/kg) on a per unit mass basis and as 300.0 MJ/m^3 on a volumetric basis. On a per unit volume basis then, atmospheric methane requires 4.30 times the energy required to pump atmospheric water into the wellhead.

These calculations can be performed for both water and methane over a range of possible source pressures (T_{in}=T_{out}=80.3°F (300 K) is assumed). Figure 2-6 contains plots of the minimum work per unit volume delivered to the wellhead for the fluids methane, water, and an incompressible liquid versus the pressure of the fluid source. The orange trace, referenced to the right hand axis, is a plot of the ratio of the minimum work per unit volume of methane to that for water versus source pressure. From these traces, methane requires much more work than water, if the sources are at low pressure; however, the required work becomes comparable at high pressure. Water behaves as an incompressible liquid throughout the range of these calculations (the water and incompressible fluid traces are nearly the same).

The discussions above are minimum work scenarios. Any real system using water or methane, due to losses, will necessarily require more energy (in the form of work) than what is predicted above.

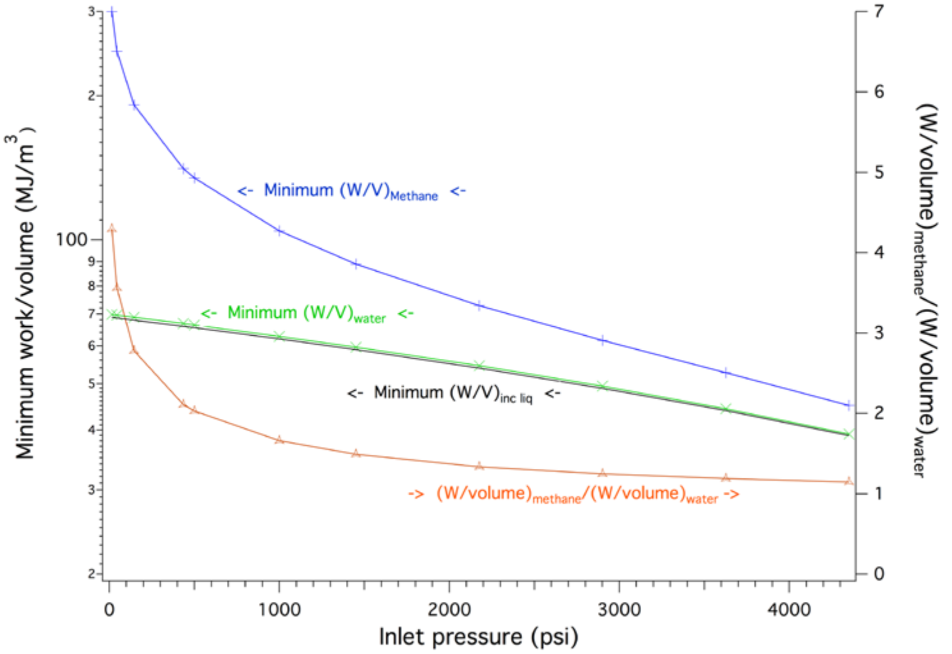

Figure 2-6. Minimum work per unit volume delivered to the Wellhead for Methane, Water, and an Incompressible Liquid (all referenced to the left hand axis) versus source pressure. The Orange Trace is the ratio of minimum work per unit volume for Methane to that for Water. The Source Pressures for the Water and Methane are assumed to be the same when determining the ratio.

Analysis of LNG to provide both cooling and fracturing fluid and a source well to provide fracturing fluid

One possible approach is to use LNG (modeled as liquid methane here) as a source of refrigeration to cool methane obtained from a nearby well and allow the compression process to occur when the fluid is in a compressed fluid state, reducing the work necessary to compress the methane to fracturing pressure. This is shown schematically in Figure 2-7. Using an analysis similar to that described above, the maximum work for such a device is shown in Figure 2-8.

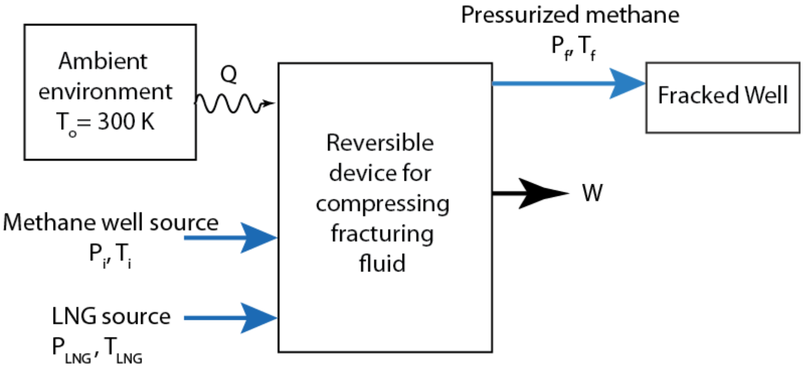

Figure 2-7. A Schematic Diagram of an Ideal Device that takes in Gaseous Methane and LNG (methane), interacts with the environment and provides high-pressure gas to the head of a gas well that is being fractured

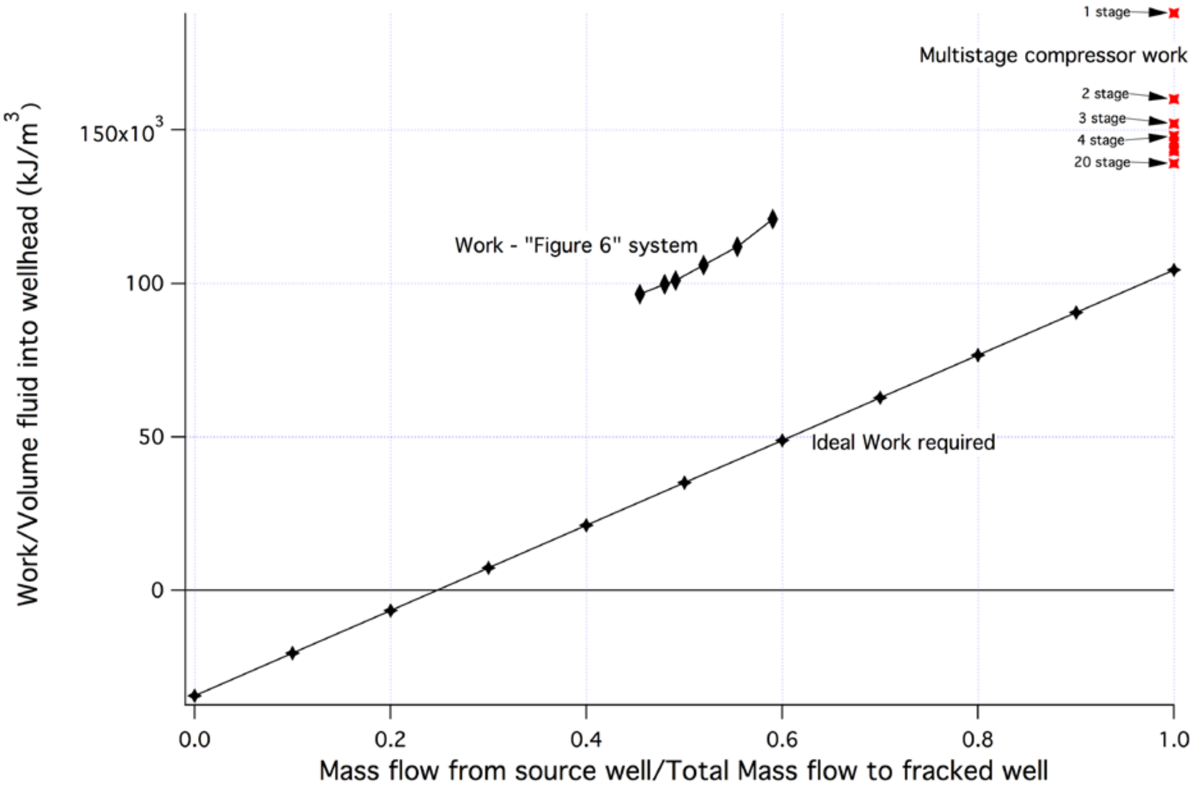

Figure 2-8. Plot of required work per unit volume of Methane injected into the Fractured Wellhead versus the Ratio of the Mass flow from the source well to the total mass flow into the Fractured Wellhead

If all of the source methane comes from the LNG source, work can be generated from the material as it is compressed and warmed to 80.3°F (300 K); consequently, the ideal work curve starts from a -912 Btu/ft^3 (-34 MW/m^3) (i.e., -912 Btu/ft^3 of work generated by the ideal apparatus) when all the methane is sourced from the LNG supply ($m_{source}/m_{tot} = 0$). In this scenario, the LNG (saturated liquid methane at 14.5 psia (1 bar) and -259.0°F (111.5 K)) is brought to a state of 80.3°F (300 K) and 10,000 psia (689 bar). It should be noted that the initial state for the source well gas assumed here is 80.3°F (300 K) and 1,000 psia (68.9 bar) and not the 500 psia (34.5 bar) assumed in the previous section.

As more methane mass is drawn from the source well (80.3°F (300 K), 1,000 psia (68.9 bar)), the ideal work required becomes positive when the mass for the source well is about a quarter of the total mass flow into the fractured well. In the extreme, where all the mass flow comes from the source well and there is no LNG consumption, the power required to deliver the methane from the source well to the fractured well is 2,791 Btu/lb$_m$ (104 MW/m^3), which can be read directly from the methane trace in Figure 2-6.

The ideal work is a lower bound for the work required to drive the system. Practical systems will always require more work to drive them than the ideal. As an example, the power required for the multi-stage compression of methane from 1,000 to 10,000 psia (68.9 to 689 bar) is included as red squares in Figure 2-8. (The compressor stages are assumed to have 80% adiabatic efficiency and the pinch temperature defect in the intercoolers is assumed to be 18°F (10 K)). Under these conditions, a three-stage compressor will need almost 150% of the energy required by an ideal system.

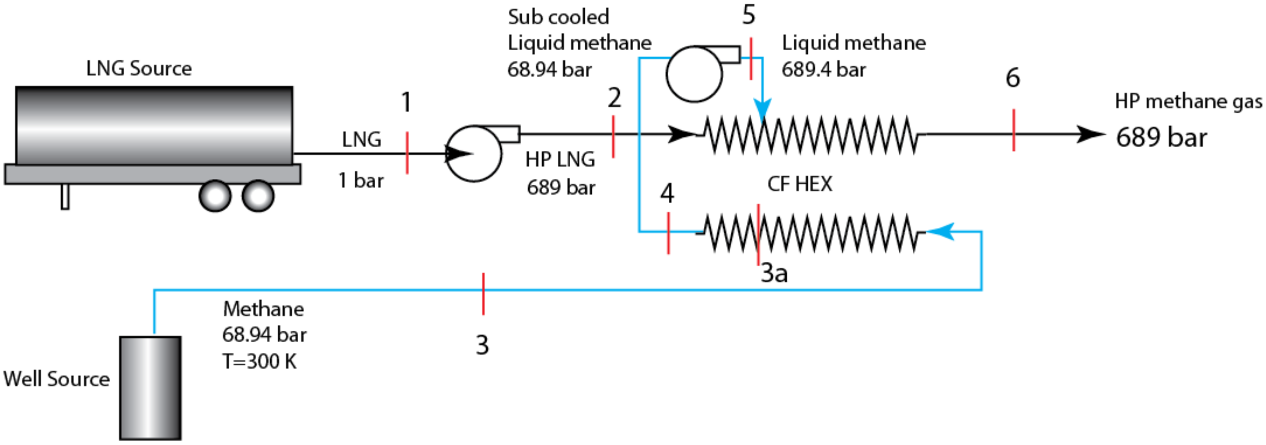

Figure 2-9. System that uses LNG to precool Gas taken from a Source Well

Another example is a system that uses LNG to cool the source-well gas prior to compression for delivery to the fractured well, as shown in Figure 2-9. Here, LNG (in state 1) is reversibly and adiabatically pumped to a pressure of 10,000 psia (689 bar) in state 2. This high-pressure fluid warms as it passes through a counter-flow heat exchanger, where it is used to precool methane from the source well. The cold, source-well methane that exits the heat exchanger (state 4) is reversibly and adiabatically compressed up to 10,000 psia (689 bar) in state 5. This fluid is then injected into the heat exchanger, where it too helps cool the incoming source-well flow. The high-temperature discharge flow from the heat exchanger (state 6) is then directly injected into the fractured well. Since both pumps are assumed to be reversible, all entropy generation occurs in the heat exchanger.

The work required as a function of the relative mass flow rate is also plotted in Figure 2-8 for this LNG-based system. A 3.6°F (2 K) temperature pinch is assumed between states 3a and 5. For the points shown in the figure, the relative mass flow from the source well varies from 0.455 to 0.59 of the overall flow and the power required varies from 2,590 to 3,248 Btu/ft^3 (96.5 to 121 MJ/m^3). The range of the ratio of the mass flow rates is restricted to ensure that both pumps are pumping liquid and not two-phase fluids.

The “in-field” power required to drive the LNG precooling system of Figure 2-9 compares well with the direct compression process. A three-stage compressor requires 4,080 Btu/ft^3 (152 MJ/m^3) where the LNG precooling system requires 2,711 Btu/ft^3 (101 MJ/m^3) (for $m_{source}/m_{tot}= 0.491$). This 30% reduction in the energy requirement in the field comes at a cost of providing almost half of the methane required by the full operation as LNG.

2.3 *Opportunities for Training and Professional Development*

During this last quarter, several of the team members attended a turbomachinery conference, ASME TurboExpo. These team members attended presentations and spoke with vendors on equipment related to this project. This allowed the team members to gain more knowledge about the commercially available equipment for the project and learn about what research is being done in the area of LNG cycle optimization.

2.4 *Dissemination of Results to Communities of Interest*

No results have been disseminated to communities of interest during this quarter.

2.5 *Plan for Next Quarter*

During the next quarter, several tasks will be completed. The list below outlines the planned work. First, the identification of the commercially available equipment for the three selected cycles will be completed. Then, the techno-economic analysis, including the thermodynamic and cost analyses, will be conducted. This will allow the top cycle to be selected. Lastly, in the next quarter, the detailed design will begin.

Summary of tasks for next quarter

- Complete identification of commercially available equipment for three selected cycles
- Complete techno-economic analysis
    - Thermodynamic
    - Cost and availability
- Begin detailed design of final selected cycle

Table 2.6. Summary of Milestone Status

Budget Period	Milestone Letter	Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments (Progress towards achieving milestone, explanation of deviations from plan, etc.)
1	A	Top 2 to 3 Thermodynamic Cycles Identified	January 2, 2015 **New: June 9, 2015**	Complete June 9, 2015	At least two combinations of thermodynamic paths and sets of equipment have been identified as being capable of accomplishing natural gas compression from approximately 200-1,000 psi inlet to 10,000 psi outlet	Completion of this milestone has been delayed by execution of full contract. Planned completion date is extended to May 12, 2015.
	B	Top Thermodynamic Cycle Identified	May 1, 2015 **New: August 31, 2015**	In Progress 40% Complete	At least one combination of thermodynamic paths and sets of equipment have been identified as being capable of accomplishing natural gas compression from approximately 200-1,000 psi inlet to 10,000 psi outlet in an economically feasible fashion. (see Milestones NOTE below). This is considered a critical path milestone.	Start of this work was delayed due to delay in execution of full contract. Planned completion date is extended to August 31, 2015.
	C	Finalized Detailed Design	September 30, 2015 **New: December 31, 2015**	Not Started	A laboratory-scale compression/pump test train will be designed to accomplish natural gas compression from approximately 200-1000 psi inlet to 10,000 psi outlet in an economically feasible fashion. (see Milestones NOTE below). This is considered a critical path milestone.	With the delay in execution of the full contract, it is anticipated that this milestone will be completed on December 31, 2015
2	D	Compressor/Pump Train Set-up Complete	March 17, 2016	Not Started	The laboratory-scale compression/pump test train will be assembled/constructed. This is considered a critical path milestone.	none
	E	Test Data Acquired and Analyzed	September 30, 2016	Not Started	Measured data will confirm that the laboratory-scale compression/pump test train is able to accomplish natural gas compression from approximately 200-1000 psi inlet to 10,000 psi outlet in an economically feasible, compact, and portable fashion (see Milestones NOTE below). This is considered a critical path milestone.	none
3	F	Field Test Set-up Complete	April 17, 2017	Not Started	The equipment for the field testing has been set-up and commissioned at the test site. The test set-up is ready for the start of operation.	none
	G	Field Test Data Acquired and Analyzed	September 29, 2017	Not Started	Measured data will show that the field-tested, laboratory-scale compression/pump train is able to accomplish natural gas compression from approximately 200-1000 psi inlet to 10,000 psi outlet in an economically feasible, compact, and portable fashion (see Milestones NOTE below). This is considered a critical path milestone.	none

3 PRODUCTS

With any technical work, results will be documented and reported to the appropriate entities. Also, the work may produce new technology or intellectual property. This section provides a summary of how the technical results of this project have been disseminated and lists any new technology or intellectual property that has been produced.

3.1 *Publications*

No written works have been published during this last quarter. Also, no abstracts for future papers or conferences have been submitted for this project.

3.2 *Websites or Other Internet Sites*

The results of this project have not been published on any websites or other internet sites during the last quarter.

3.3 *Technologies or Techniques*

No new techniques or technologies have been developed in the last quarter.

3.4 *Intellectual Property*

Two innovative cycles were developed during the last quarter. These include the Pre-Compressed Methane Liquefaction Cycle and the Mixed Refrigerant Cycle with High Pressure Cooling. Both of these cycles are discussed above in the Accomplishment section. SwRI and SLB intend to submit patent applications on both of these cycles in the following quarter.

4 PARTCIPANTS & OTHER COLLABORATING ORGANIZATIONS

The work required to develop the high-pressure natural gas (sCH_4) processing system for fracturing requires the technical knowledge and effort of many individuals. Also, two companies, SwRI and SLB, are partnering to complete the work. This section provides a summary of the specific individuals and organizations who have contributed in the last quarter.

4.1 *Southwest Research Institute (SwRI) – Prime Contractor*

The following list provides the PI and each person who has worked at least one person-month per year (160 hrs of effort) in the last quarter.

- Melissa Poerner, P.E.
    - Project Role: Principal Investigator
    - Nearest person month worked: 1
    - Contribution to Project: Project management, thermodynamic cycle review, identification of commercially available equipment
    - Funding Support: DOE
    - Collaborated with individual in foreign country: Yes (not related to this project)
    - Country(ies) of foreign collaborator: France
    - Traveled to foreign country: Yes (not related to this project)
    - If traveled to foreign country(ies), duration of stay: France (13 days) and Canada (6 days)

- Griffin Beck
    - Project Role: Project Engineer
    - Nearest person month worked: 1
    - Contribution to Project: thermodynamic cycle analysis, identification of commercially available equipment
    - Funding Support: DOE
    - Collaborated with individual in foreign country: Yes (not related to this project)

  - Country(ies) of foreign collaborator: France
  - Traveled to foreign country: Yes (not related to this project)
  - If traveled to foreign country(ies), duration of stay: France (5 days)

4.2 *Other Organizations*

In this project, SwRI is collaborating with Schlumberger (SLB). SLB is a subcontractor and cost share supporter for this project. More information about their participation is listed below.

- Schlumberger
  - Location of Organization: United States
  - Partner's Contribution to the Project: Analysis and design support
  - Financial Support: n/a
  - In-kind Support: Labor hours in first budget period
  - Facilities: n/a
  - Collaborative Research: SLB staff supports the analysis and design tasks for the first budget period
  - Personnel Exchanges: n/a

5 IMPACT

During this quarter, more analysis of different thermodynamic cycles was conducted. Two innovative cycles were identified: Pre-Compressed Methane Liquefaction and the Mixed Refrigerant Cycle with a modification to have high pressure cooling. Both of these cycles can provide industry with an optimized method for creation of high-pressure methane or for use in LNG production.

6 CHANGES/PROBLEMS

During the first quarter, the full contract was not completed. Therefore, this delayed the start of the technical work. During the second quarter, the technical work was started and attempts were made to accelerate the work pace. Based on the work completed during the second quarter and the workload anticipated for the rest of the first budget period, the schedule for the project was adjusted. The completion date for the milestones in the first budget period were shifted as outlined below and in Table 2.6. It is anticipated that the project work for the first budget period will be completed on December 31, 2015, which is three months after the original due date (September 30, 2015). A No-Cost Time Extension request was submitted to DOE in order to extend the project deadline.

- Milestone A – Top 2 to 3 thermodynamic cycles identified
  - Original Completion Date: January 2, 2015
  - New Completion Date: June 9, 2015
- Milestone B – Top thermodynamic cycle identified
  - Original Completion Date: May 1, 2015
  - New Completion Date: August 31, 3015
- Milestone C – Finalized Detailed Design
  - Original Completion Date: September 30, 2015
  - New Completion Date: December 31, 2015

7 BUDGETARY INFORMATION

A summary of the budgetary data for the project is provided in Table 7.1. This table shows the initial planned cost, the actual incurred costs, and the variance. The costs are split between the Federal and Non-Federal share.

For the third quarter in budget period 1, $95,650 was spent. The cost included labor charges and charges for travel for the face-to-face meeting in April at Southwest Research Institute. Since the technical work began in February 2015, the cost variance on the project costs is high. The schedule for the project was shifted approximately 4.5 months. A review of the planned costs for Q2 show that the spend rate from Q2 closely matches the actual spend rate in Q3. This indicates that the technical work is progressing as planned with an offset because of the delayed start in technical work.

Table 7.1. Budgetary Information for Period 1

Baseline Reporting Quarter	Budget Period 1			
	Q1	Q2	Q3	Cumulative Total
	10/1/2014 - 12/31/2014	1/1/2015 - 3/31/2015	4/1/2015 - 6/30/2015	
Baseline Cost Plan	$112,000	$103,000	$138,000	$353,000
Federal Share	$89,600	$82,400	$110,400	$282,400
Non-Federal Share	$22,400	$20,600	$27,600	$70,600
Total Planned	$112,000	$103,000	$138,000	$353,000
Actual Incurred Cost	$15,754	$49,772	$95,650	$65,525
Federal Share	$15,754	$37,203	$64,228	$52,957
Non-Federal Share	$0	$12,569	$31,422	$12,569
Total Incurred Costs	$15,754	$49,772	$95,650	$65,525
Variance	$96,246	$53,228	$42,350	$149,475
Federal Share	$73,846	$45,197	$46,172	$119,043
Non-Federal Share	$22,400	$8,031	($3,822)	$30,431
Total Variance	$96,246	$53,228	$42,350	$149,475

8 REFERENCES

1. "LNG/CNG Solutions," GE Oil & Gas, http://biogassydostraskane.se/wp-content/uploads/2013/07/CNG-solutions-short.pdf, 2011.

2. "CryoBox – Nano LNG-Station," Galileo, http://www.galileoar.com/en/lng, 2014."Distributed Small-Scale LNG," Dresser-Rand, http://lng.dresser-rand.com/docs/2336_LNGo_01312014.pdf, 2013.

4. Nezhad, S., et al., "Thermodynamic Analysis of Liquefied Natural Gas (LNG) Production Cycle in APCI Process," *Journal of Thermal Science*, vol. 21, no. 6, pp. 564 to 571, 2012.

5. "Refrigeration Basics and LNG," University of Oklahoma, http://www.ou.edu/class/che-design/che5480-07/Refrigeration%20Basics%20and%20LNG.pdf, accessed January 2015.

6. "Air Products' full range of liquefaction process options" Air Products Brochure, http://www.airproducts.com/~/media/Files/PDF/industries/lng/lng-air-products-full-range-of-liquefaction-process-options.pdf, 2013.

7. Pak, J., "Nitrogen Expansion Cycle Enhances Flexibility of Small-Scale LNG," *Gas Processing*, July 2013.